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A Force Sensor System

for the Robotuna Project

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1.0 Introduction

Underwater vehicles have many uses in civilian as well as military marine operations. Their applications range from maintenance and inspection on oil rigs to underwater salvage operations, and from scraping barnacles off the hulls of ships to searching a hostile bay for mines. For such vehicles to carry out their tasks it is advantageous to have high propulsive efficiencies. Efficiency for an underwater vehicle is measured by recording the amount of energy required to pull the vehicle through the water at a certain velocity and comparing that to the energy which the vehicle must expend to propel itself at the same velocity.

Propellers are the primary conventional mechanism for water-based propulsion. The efficiency of a propeller scales up with specific load. This means that while a propeller works well on a vehicle with large available diameter, like a submarine, it has a rather limited efficiency for smaller autonomous vehicles where propellers must fit in cramped spaces. Additionally, a submarine requires a distance several times its length to turn, even at slow speeds, while fish can turn at full speed in a fraction of their length.

Such limits are inherent in the use of propellers and place drastic restrictions on the range, speed, and application of current underwater vehicles.

Fish represent one of nature's best solutions to the problems of underwater travel. Tuna cruise across the ocean at high speeds and many fish maneuver in and out of tight corners. The Robotuna project is an attempt to replicate these skills by emulating the form and motion of the tuna.

1.1 Statement of Scope

The Robotuna project is an experiment to study the swimming efficiency of an underwater vehicle using fish-like propulsion. To measure this efficiency it is necessary to have an accurate array of force sensors inside the vehicle. This paper describes two iterations of the development of force sensors. The first implementation proved untenable for measuring efficiency and has since been redesigned to overcome previous limitations. The second iteration is currently under construction constructed at the MIT Testing Tank. With accurate force sensors in place the Robotuna project can progress to the final stage

of fine tuning swimming patterns and other parameters for maximum efficiency.

1.2 Report Preview

This paper is organized into five parts: introduction, background, methods, results, and conclusion. The Introduction summarizes the need for the project. The Background section describes the original project plan. The Methods section documents the original implementation of the force sensor system. The Results section includes what went wrong and how it was detected. The Conclusions section encompasses the revisions and corrections, also describing the current status of the project.

1.3 Review of relevant literature

The Robotuna project has been covered in Scientific American [Reference 1]. Research leading up to the project has been conducted using flapping foils [References 2, 3]. Foil-shaped fins were placed in a small tank and moved in a flapping motion designed to generate propulsion in a manner similar to swimming. This apparatus was subject to force analysis

and high speed video recording of dye dissolving from the foils and particle displacement from laser illumniation of fluorescent particles in suspension. The the flapping foil experiments achieved a maximum propulsive efficiency of 87%, significantly better than the theoretical maximum efficiency of a propeller. It is hoped that even greater efficiencies will be recorded from the Robotuna Project due to the replication of fish features not present in the flapping foil experiments.

2.0 Background

Nature has created a near perfect solution to the problems of underwater travel. The Robotuna is designed to be a simplified model this super-efficient fish. To make the implementation of this project more feasible several important aspects of underwater travel were exempted from the scope of the Robotuna project. These simplifications are documented in the following paragraphs.

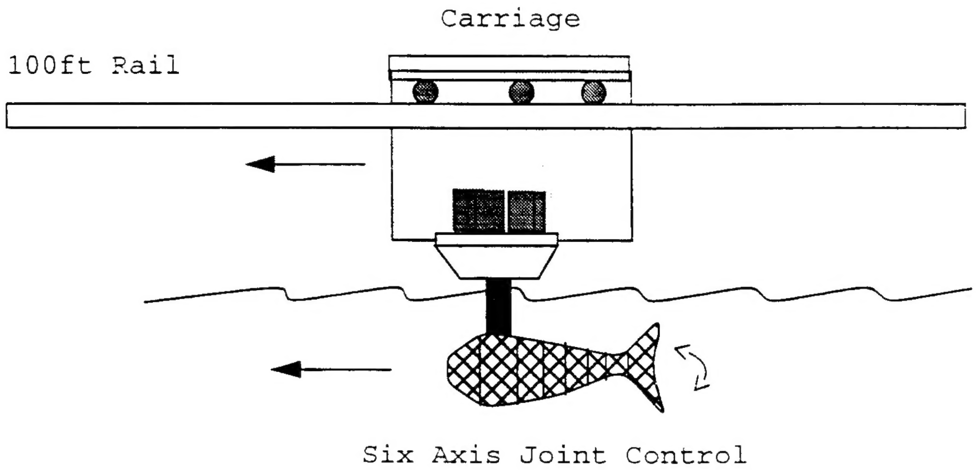
Navigation is a difficult control problem that is far beyond the scope of this project. Buoyancy is

another variable that adds complexity to the design of underwater vehicles. The stability issues and complex feedback control techniques for navigating in an underwater environment are not necessary for the emulation of simple propulsive swimming motion. For this reason a center pivot was designed into the Robotuna such that it is constrained to linear motion as seen in Figure 1.

This center pivot simplification was justified by the detailed observance of bluefin tuna in the New England Aquarium in Boston, MA. A point on the body of the tuna close to the head undergoes very little side-to-side motion as the bluefin swims. This body section of the Robot fish is fixed to a swivel platform on a moving carriage. The servomotors which control the tuna are mounted on the platform as well such that they can turn with the tuna.

The dimensions of the MIT Testing Tank are 100 feet long by 8 feet wide by 4 feet deep. The Robotuna has been mounted on a carriage which travels the length of the tank [Figure 1].

Figure 1: Robotuna mounted on the Carriage

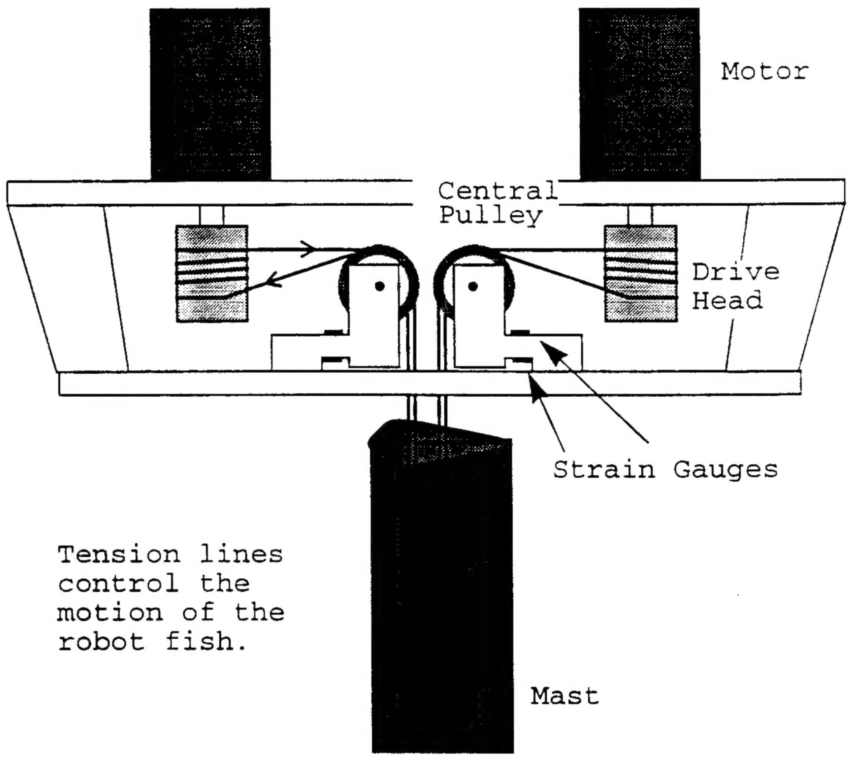


Using data from the observance of swimming tuna and tuna anatomy, a simplified skeletal model was developed that employed seven joints between the seven body sections and the tail. This model was linked to a bank of six servomotors that articulated the swimming motion. Only six servomotors were necessary. The head joint and first body joint were linked mechanically because the observations indicated that the two joints would always move simultaneously in normal swimming.

Due to concern about mounting large high-voltage servomotors in waterproof housings inside the tuna body, the motors were placed on a platform attached to the carriage that could rotate with the robot fish. Position control from the servomotors was translated to the joints inside the tuna using a set of aircraft

tension cables and a complex array of pulleys. The servomotor mounting area is depicted in Figure 2.

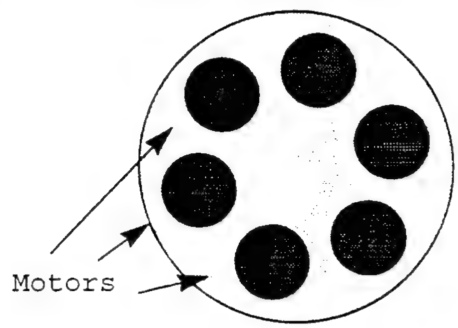
Figure 2: Servomotor Mountings (side view)



The tuna's original force sensors [Figure 2.] measure the strain on the aluminum mountings that hold the central pulleys. This strain was intended to be the summation of the tensions on the cables that lead to and from the drive head of each servo-motor. As the servomotors turn their drive heads in either direction, the tension on the cables changes to reflect the forces on the axes of the fish. Six servomotors are mounted in

a hexagon pattern around the central mast. [Figure 3.] A central mast fixes the body of the tuna to the carriage and protects the aircraft tension cables.

Figure 3: Servomotor Mountings (top view)



Signals from the amplifiers travel on cables that link the moving carriage to an array of computers on the Bridge (See Appendix A). The computers are connected over a local area network to facilitate communication and link these systems for batch trials. A computer on the bridge is in control of the motorized carriage and can be operated manually or by an automated program.

One of the bridge computers is equipped with an analog-to-digital conversion board that can read the signals from the amplifiers and convert them into a digital form which the computer can process. The signals are stored on the computer's hard drive during each swimming trial. After the data are collected

a Matlab program loads the data, filters it, and computes the amount of energy put into propulsion by the servomotors.

3.0 Methods

The circuitry used to process the signals from the strain gauges was custom built for cost effectiveness. Because off-the-shelf load cells and amplifiers range from $400 to $5000 each, the decision was made to apply the strain gauges in-house and to develop custom amplification and signal conditioning circuitry.

Strain gauges were applied to six pulley mount components illustrated in Figure 3. The gauges were then wired to simple amplification circuitry that magnified the signal 5000 times. The circuitry included the capacity for adjustment to calibrate the offset, or 'zero' the sensors.

An additional force sensor measures the thrust/drag of the tuna. Only one such sensor was required, so a high quality off-the-shelf component was used.

Little filtering was used since high frequency noise was observed to be less than 2% of the amplified signal. This is attributed to fact that the wires between the strain gauges and the amplification circuitry were only a few feet long.

Drift was a more significant problem, but the chosen method for compensation was shared between hardware and software. To compensate for drift the internal adjustments were calibrated on a weekly or monthly basis to bring the outputs into the range of the A/D hardware. For precise drift compensation for each trial, the software was written to monitor the quiet period at the beginning of each trial and to subtract the average offset signal from the remainder of the data. In this way, the precision calibration occured during each trial insided the computer, causeing the datat to be less accurate due to the need for a wider dynamic range in hardware.

It was anticipated that there would be a future point where signal multiplexing would be useful; hence circuitry was developed in anticipation of this need. A multiplexer and decoder were constructed. This allowed the transmission of up to 15 signals over three wires instead of requiring 16 wires (including ground). This saved the trouble of connecting many-wired cables between the systems. The multiplexer worked by using one channel for a clocking signal, while the other channel was switched between the 15 signal lines. The decoder generated the clock which synchronized a counter on multiplexer. The decoder used sample-and-hold components to store each of the 15 signals that cycled over the signal wire.

The clock cycled the counters through channels at a rate of 1000 Hz. This resulted in a decoder output that correlated to within 50 millivolts of the multiplexer input, and an update rate greater than the sampling frequency of the analog-to-digital converter at the bridge.

4.0 Results

There are three factors that rendered the original force sensing system inadequate: summation, dynamics, and placement.

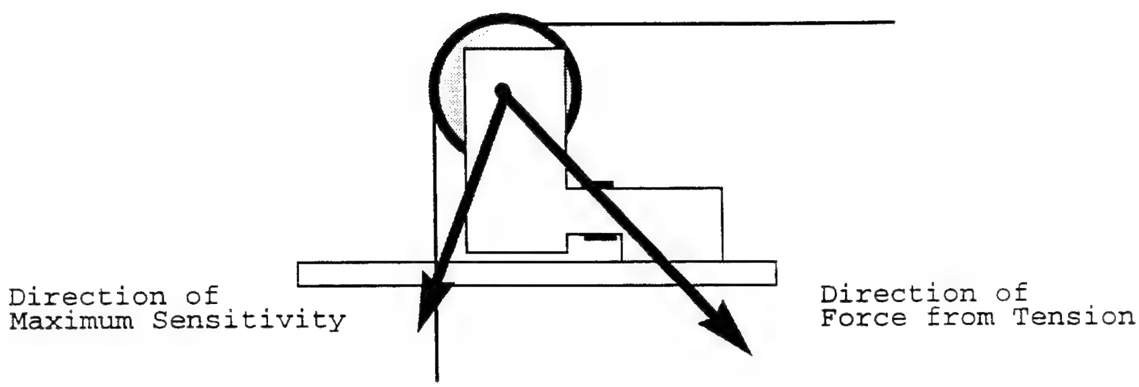
The main problem with the original approach was that only six sensors were used to measure cable tensions. Each sensor measured the sum of the tension on the incoming and outgoing cables that wound around the drive head of the servomotors. It was thought that the total energy being put into the system could be taken from the simple summation of the forces on pulling cables. As it turned out, this summation of tensions, measured at the drive head, was unable to give an accurate report of the energy consumption of the system.

Another difficulty with this system was that it did not take into consideration the dynamics involved in transmitting force over the tension cables. Swimming is a periodic motion with oscillations at frequencies that can range from .5 to 10 Hz.

The tension lines driving the tuna are subject to the dynamics of motion relating masses and springs with damping.

Additional problems are related to the mounting of the strain gauges on the pulley. The force vector generated by tension on the two cables is not aligned with the direction of maximum sensitivity. [Figure 4.] This means that the sensor is more sensitive to mechanical noise and may behave in a non-linear manner.

Figure 4: Force Sensitivity of Original Sensors



Another mounting problem was that the sensors were placed very close to the servomotors, which operated by turing rapidly in small steps. This step-like motion created transient spikes in the recorded strain. These transients interfered with the force signal and would give an artificially high reading for the averaged energy from the servomotors. A simple low-pass filter could not remove such spikes since smoothing the signal would still cause the integral to be greater than the actual value.

5.0 Conclusions

The results of preliminary tests showed that a re-thinking of the force sensor system was necessary. The strain guage sensors have been re-designed and will be implemented by June, 1995. Three primary changes are being made to the force sensor system: measurement of each individual cable, movement of the sensors to inside the tuna, and the addition of circuitry for automatically calibrating the sensors before a trial.

The most significant change in the force sensor system is to double the number of force sensors. Each of the twelve tension cables connecting the servomotors to the fish actuators will be monitored with a separate force sensor.

The second design revision is that the sensors will not be measuring the force above the waterline where it is convenient. Instead, they will be placed underwater, inside the tuna, and as close to the actuators as possible. This will reduce the effects of the mass and spring dynamics that were problematic in the previous system. A diagram of this sensor is located in Appendix D.

The strain gauge amplifiers were easy to calibrate in the original design because they were located above the waterline. To keep wiring to a minimum, the multiplexer will be underwater along with the amplification circuitry. The amplifiers will be

much more difficult to access for calibration. For this reason a revised amplifier design has been tested which uses a single adjustment for calibration at the time of installation and only requires a signal from the computer to perform the precision calibration needed before each trial. This circuit has been implemented on a printed circuit board (PCB) using small surface mount components.

Surface mount PCB fabrication was chosen over the previous wire-wrapping techniques because it is easier to replicate printed circuit boards in large quantities and for interchangeable components. The new circuits have one simple connector which will allow twelve amplifiers to be placed close together to fit inside the nose cone. The connector insures the modularity of the system for easier upgrading should the circuit design be revised. The switch to printed circuit board fabrication has reduced the time for building and testing a single strain gauge amplifier from approximately 8 hours to 30 minutes. Several amplifiers of the new design have been fabricated and are being evaluated.

The multiplexer/decoder pair has proven to be quite reliable and has operated without trouble for 8 months. Even though the primary purpose of developing the Muxltiplexer was for later applications, the planned modifications to the force sensor system will benefit greatly from the application of this cir-

cuitry. Amplification circuitry is being moved to the nose cone of the tuna and the available space for running cabling through the mast is very small (.4 inches in diameter), thus it is very useful to be able to send many signals over a small number of wires.

The multiplexer has been redesigned to operate under computer control and no longer requires a decoder. The computer sends out four binary signals to select one of fifteen channels. In addition, the sixteenth combination is reserved for triggering the auto-zeroing circuitry on the sensors. Since the computer has multiple analog inputs this system can be scaled up easily by adding additional multiplexed wires which each carry fifteen signals.

5.1 Future Plans

Other aspects of the Robotuna project are also undergoing design revisions. These include position sensors, tuning the controller, and additional fins. These systems will be integrated over then next several months and refinements will be made to the swimming algorithm over the summer. The data from swimming trials will yield an efficiency number for

the propulsive efficiency of the tuna. The project is expected to be completed before August 1995.

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Appendix A: Bridge and Carriage Layout.